Using the Dilatometer Test to Make Accurate Settlement Predictions

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ABSTRACT: To make accurate settlement predictions, the engineer must measure the soil's stiffness. Dilatometer tests statically deform the soil at intermediate strain levels and have excellent correlations with the constrained deformation modulus of the soil. Standard penetration tests and cone penetration tests that engineers sometimes use do not have good correlations with deformation modulus because they are penetration tests that strain the soil to failure. One hundred and twenty nine case studies show buildings that were redesigned with shallow spread footings based on the dilatometer test data saved $25,053,000 than the original overly conservative design based on other less accurate tests.

Keywords: Dilatometer test; settlement; standard penetration test; cone penetrometer test; pressuremeter test; laboratory consolidation test; foundation redesign

1. Introduction

Often soil has enough stiffness to safely support a structure and prevent the structure from settling an unacceptable amount, but engineers using poor measurements will likely design unnecessarily costly foundation systems. The stiffness of soil or deformation modulus can range over several orders of magnitude and therefore needs a high quality test to accurately determine its value. The dilatometer test (DMT) is a calibrated static deformation test that accurately measures the soil's deformation modulus. Unfortunately, too often engineers use other tests that they are more familiar with or have lower unit costs to attempt to predict deformation modulus. These other tests have critical flaws resulting in inaccurate settlement predictions. One hundred and twenty one (125) case studies show how the geotechnical consultant used dilatometer tests to redesign foundations much more economically than originally designed with poorer prediction tests.

2. Dilatometer test for settlement

Often, soils that can settle can also be penetrated by pushing a probe into them. Soil can exhibit a wide range of stiffness. The dilatometer test is a calibrated deformation test that accurately measures the soil's stiffness. DMT tests are commonly performed at 20 centimeter (8 inch) intervals (5 tests per meter long push rod) for the full depth of the test sounding, giving the engineer a vivid picture or profile of soil stiffness versus depth. The engineer can easily identify trends in soil stiffness and any soft layers. Sometimes the site has thin soil layers that compress and need near continuous testing to properly characterize them. If a thin soft soil layer is found, then testing at 10 centimeter (4 inch) intervals will provide additional valuable modulus data for this critical layer.

For each test depth, the operator inflates the membrane outward, first measuring the pressure where the membrane lifts off from the blade ("A" reading) and the pressure where the membrane is fully expanded (1.1 mm from the blade) ("B" reading). The operator should measure the thrust needed to advance the blade to the test depth. Before starting the DMT test, the operator can compare the thrust measurement with previous thrust data and their corresponding dilatometer "A" and "B" readings, helping him/her predict what the dilatometer "A" and "B" readings may likely be. The ratio of "B"/"A" is approximately the same for the same soil type. For cohesive soil that ratio is about 1.5, while for cohesionless soil that ratio is about 3. After measuring the "A" reading, and if the thrust is similar to the previous value, the operator can assume that the soil type is likely similar and its "B"/"A" ratio is the same. The operator can now make a good estimate of the "B" reading. The operator should inflate the membrane more slowly as the pressures approach predicted "A" and "B" values, measuring those values more accurately. Where thrust measures less than 500 kgf, which generally indicates a very soft soil, the operator should reduce the test depth interval to 10 centimeters to provide more data for design in these critical soils.

Below the groundwater table, the operator can deflate the membrane and measure the pressure ("C" reading) where the membrane deflates and recontacts the blade. Below the groundwater table, the "C" reading measures the hydrostatic groundwater pressure in a cohesionless soil and the "C" reading measures excess pore water pressures in a cohesive soil (Schmertmann and Crapps, 1988). In cohesive soil, if the operator measures either "A" or "C" readings versus elapsed time, the time rate of consolidation can be computed as the pore pressures dissipate over time.

When the dilatometer blade is pushed into the soil, the geometry of the blade causes minimal volumetric and shear strain to the soil. In contrast, when the cone penetrometer is pushed or standard penetration test split spoon is driven into the soil, their circular geometry causes significantly more volumetric and shear strain to the soil. Figure 1 illustrates the differences in the straining of the soil due to their different geometries (Baligh, Scott, 1975). Marchetti (1998) shows that arching occurs when pushing a circular probe, while the dilatometer blade knifes into the soil with little arching effects, resulting in more accurate stress history measurements (Figure 2).

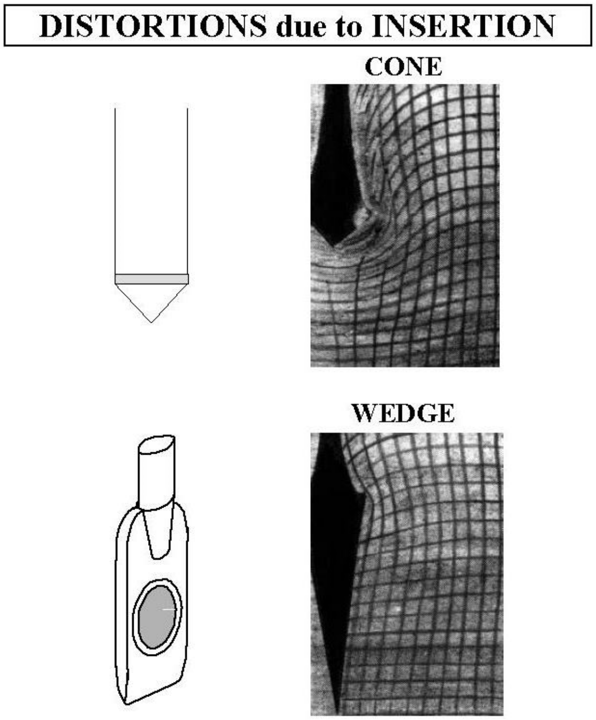

Figure 1. : Less disturbance pushing the DMT blade than conical probe (CPT or SPT)

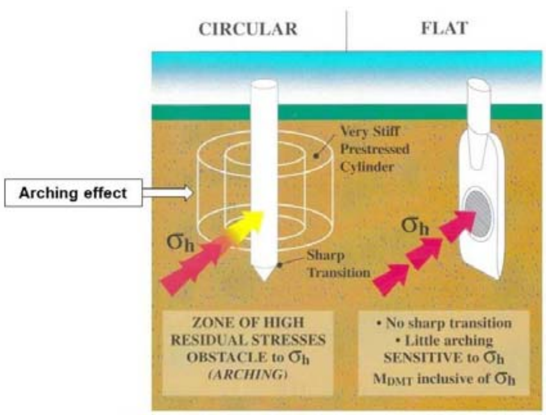

Figure 2. : Significant arching caused by pushing conical probe versus little arching by pushing sharpened blade that knifes into the soil

The dilatometer "A" and "B" readings are corrected for the membrane stiffness in air, "ΔA" and "ΔB", to get "P_0" and "P_1" values. The "P_0" and "P_1" values then compute the dilatometer indices, I_D (Material Index), K_D (Horizontal Stress Index) and E_D (Dilatometer Modulus). These multiple independent indices converge with accurate correlation equations to the desired soil property. Dr. Silvano Marchetti often described this method of creating correlation equations as "triangulation"--using two or more independent variables to hone in on a third dependent parameter. The constrained deformation modulus depends on the soil type and stress history. Silvano Marchetti (1980) correlated the dilatometer modulus, E_D, with I_D (soil type) and K_D (stress history) to get accurate values of the constrained deformation modulus. Failmezger and Bullock (2004) show on Figure 3 how well the constrained deformation modulus from dilatometer data compared with laboratory consolidation test data.

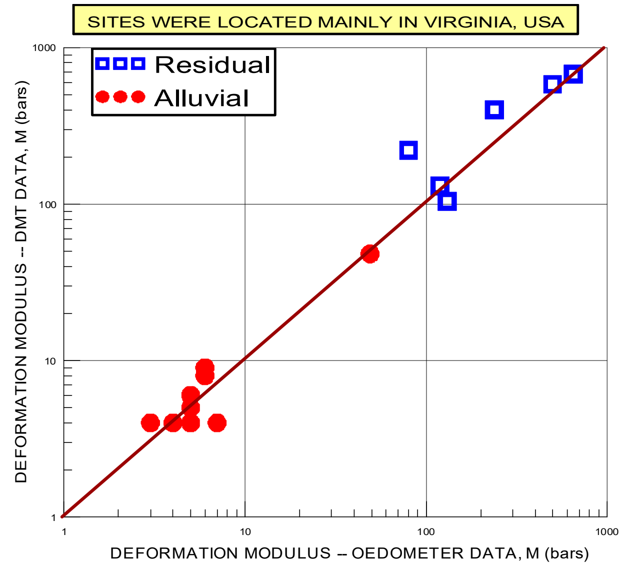

Figure 3. : Comparison of DMT M values and Laboratory M values

Schmertmann (1986) developed a method to compute settlement based on dilatometer data. He also made comparisons of 16 cases, showing how well the dilatometer predicted amount of settlement compared to what actually occurred. Hayes (1986), using Schmertmann's method, shows excellent comparisons at five sites. Figure 4 (Failmezger, Bullock 2004) plots these settlement comparisons.

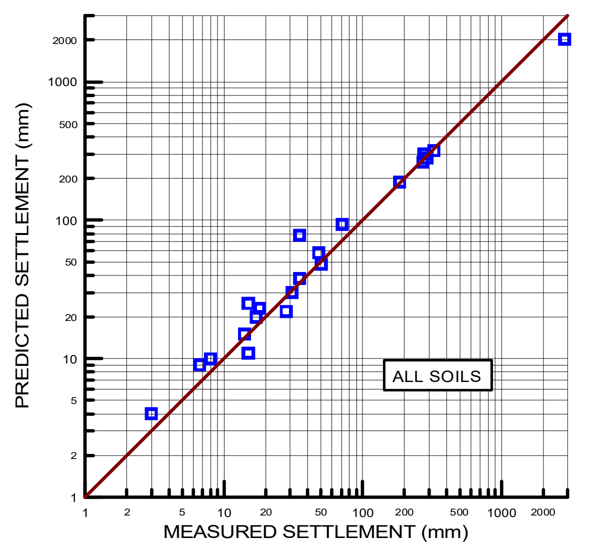

Figure 4. Comparison of predicted versus measured settlements

Godlewski (2018) also compared predicted settlement with measured settlement at various sites in Poland as shown on Figure 5. Godlewski used numerical methods for predicted settlement analyses.

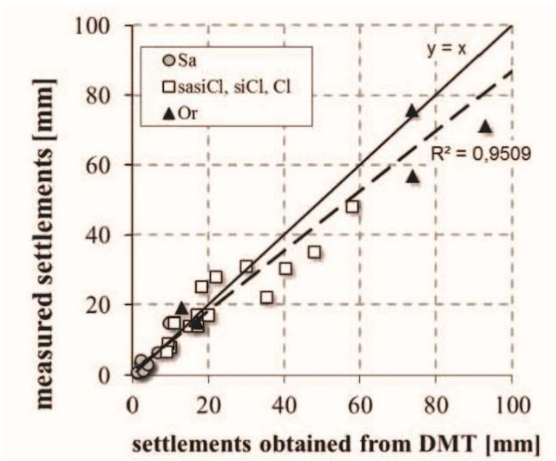

Figure 5. Comparison of predicted versus measured settlement at various sites in Poland

3. Drawbacks of settlement predictions from other tests

Engineers often use other less accurate tests, namely the standard penetration test (SPT) and the cone penetrometer test (CPT), for settlement predictions that tend to over-predict settlement (sometimes grossly) and lead to costly design recommendations. Engineers may use the SPT and CPT because these tests are more readily available, and they have experience using them. However, engineers should strive to make accurate settlement predictions, and they should use deformation tests instead of penetration tests to predict the soils' deformation properties, which should be rather intuitive. .

3.1. Standard Penetration Test (SPT)

The driller creates a hole with either hollow-stem flight augers or mud rotary drill bits to the test depth. Mud rotary methods fill the drilled borehole with drilling mud and restore about half of the original geo-static stress, while hollow-stem augers remove all of the geo-static stresses. As a result, hollow-stem augers disturb the soil more than mud rotary methods. The driller dynamically drives a 2 inch (51 mm) outside diameter split spoon sampler 18 inches (450 mm) below the borehole counting the number of blows to drive it every 6 inches (150 mm) with a 140 pound (63.5 kgf) hammer dropping 30 inches (750 mm). The driller and sometimes an inspector meticulously count these blows. However, the energy needed to drive the sampler is rarely calibrated and depends on the hammer type, (donut, safety or automatic trip) and the physical condition of the hammer or physical/mental condition of the driller. While they may accurately measure the number of blows, they often do not know how hard the sampler is struck!

The dynamic driving of the sampler may measure the dynamic soil properties better than its static properties (Schmertmann, 1978). Additionally, the penetration strains the soil to failure, while the proposed structure strains the soil to an intermediate level. The dynamic failure straining of the soil does not model the deformation properties of the soil needed for design.

When the sampler penetrates the soil, its circular projection disturbs and remolds the soil. Residual soil has latent rock structure present, but the dynamic penetration from the SPT spoon destroys it and does not measure its beneficial stiffness gain. In a sensitive cohesive soil, the soil structure is again destroyed as its stiffness now resembles a remolded soil rather than an intact soil.

3.2. Cone Penetration Test (CPT)

The cone penetrometer probe quasi-statically pushes into the soil at a constant rate of 2 centimeters/second, accurately measuring the tip resistance with calibrated strain gauges. Unlike the SPT, the CPT accurately measures penetration resistance. A computer collects that data at depth intervals of 1 to 5 centimeters, depending on the depth measuring device.

The constrained deformation modulus is empirically correlated to the CPT tip resistance by multiplying the tip resistance by α. However, values of α range from 2 to 25 and depend on soil type, stress history, and ageing (Baldi, et. al., 1988). Figure 6 illustrates the wide range of α factors. The CPT is a single parameter test for predicting deformation modulus and requires stress history data. The engineer should preferably use either site specific or at least geologic formation specific correlations with lab or field deformation test data, to determine better values for α. While these correlations improve the settlement prediction, they serve as an additonal source of uncertainty and prediction error.

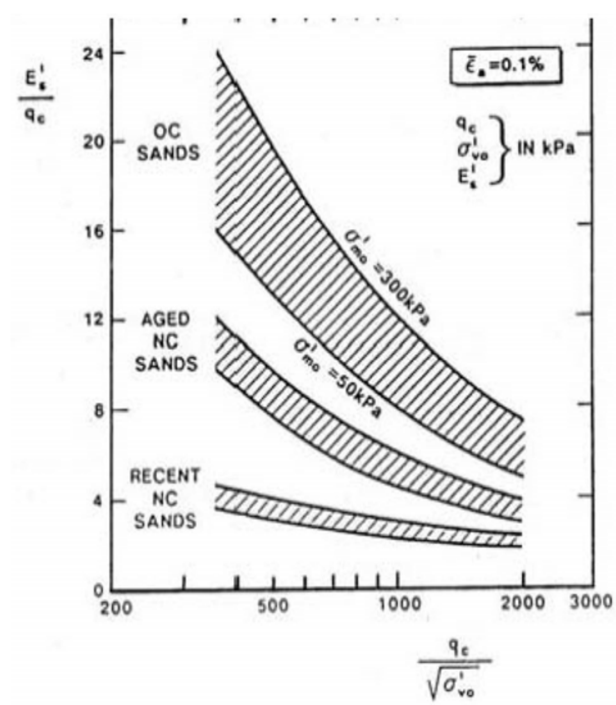

Figure 6. CPT Correlation coefficients for deformation moduli in cohesionless soil

When ground improvement methods are used on a project to improve the deformation modulus, the horizontal stresses can increase significantly. The CPT is not sensitive to these changes in stress and the α factor can double from its original value as a result of ground improvement (Figure 7).

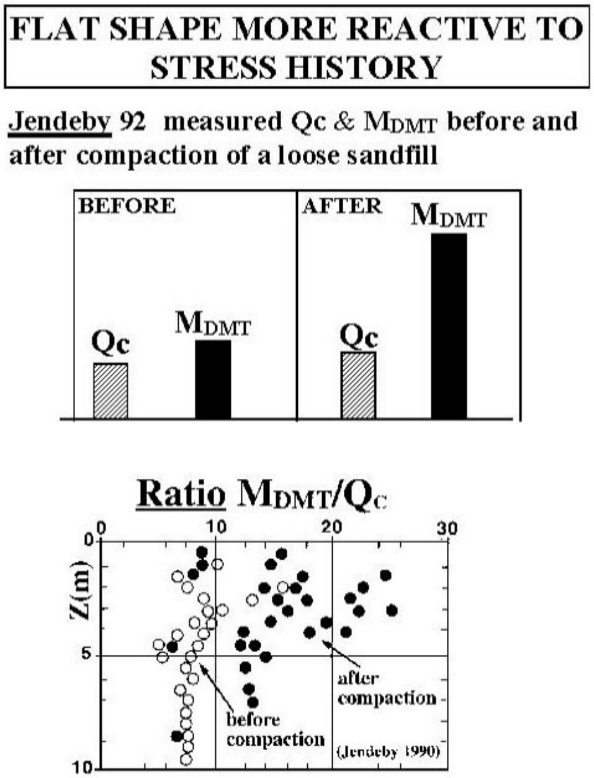

Figure 7. Ground improvement changes the α factor

Like the SPT, the CPT suffers similar inaccuracies. The CPT strains the soil to failure and its projected circular shape disturbs the soil (Figure 1).

3.3. Soil Pressuremeter Test (PMT)

Like the DMT, the soil pressuremeter test (PMT) statically deforms the soil and accurately measures its deformation modulus. Unlike DMT that takes about 1 minute to perform, PMT takes about 1 hour to perform. Unlike the DMT, which are commonly performed at 0.20 meter depth intervals, PMT are performed at 1 to 3 meter intervals. Due to most project budgets, pressuremeter tests are performed at pre-selected locations, while the DMT are performed as profiling modulus tests. However, the pressuremeter can test very strong soil and rock that DMT cannot push into. When a pressuremeter is placed inside a slotted steel casing, tests can be performed in formations that contain gravel and occasional cobbles, which cannot be tested with DMT.

The quality of the pressuremeter test depends on the quality of the borehole that it tests. While drillers usually drill to minimize disturbance to the bottom of the borehole for SPT, the engineer needs to train them to drill to minimize disturbance to the sides of the borehole. In general, to make a good pressuremeter test hole, the driller should use a properly sized bit, roller cone bit for cohesionless soil or drag bit for cohesive soil, rotation rate of 60 rpm, mud flow rate of 10 gallons per minute (40 liters per minute), and a feed rate of approximately 1 foot/minute (0.3 meters/minute).

With accurate pressuremeter tests in fairly homogeneous formations, where a few tests are enough to measure the deformation modulus, the engineer can make accurate predictions of settlement.

3.4. Laboratory Consolidation Test

The laboratory consolidation test serves as a fundamental method of determining the soil's deformation modulus. However, its results depend on the quality of the "undisturbed" soil sample. The driller should use a piston sampler to minimize disturbance. With piston samplers, one has difficulty obtaining undisturbed samples in very soft clays and in cohesionless soil. With the new Gelcoat piston sampler, high quality samples can be obtained in these otherwise difficult to sample soils. When the shear wave velocity of the sample measured with bender elements compares favorably with the field measurement of the shear wave velocity, then the engineer has obtained a high quality sample (Huang, 2016). Like the soil pressuremeter tests, due to its high unit costs, it is used only at selected locations and not as a modulus profiling tool. Again like pressuremeter tests, if only a few tests are needed to determine the deformation properties, then the engineer can make accurate predictions of settlement.

4. Redesign of several projects using dilatometer test data

One hundred and twenty nine (129) projects demonstrate how dilatometer test data saved the owner significant money ($25,053,000) with their foundation designs over previous overly conservative designs based on other inferior tests. Table 1 shows the approximate amount of money that the owner saved. For many cases the geotechnical engineer persuaded the owner to perform dilatometer tests for more accurate design and lower construction costs. For some cases the original geotechnical engineer provided a costly design based on inferior tests, and the astute owner thought that the initial design seemed too costly. The owner sought a second opinion, and the second geotechnical engineer performed dilatometer tests to better analyze and predict the settlement that would occur under the anticipated structural loads. In each case the dilatometer data predicted tolerable settlement with shallow spread footings that would safely support the structure. To date, none of these buildings show any distress or cracks.

Table 1. Cost savings by using DMT to redesign the foundation system

PROJECT NAME	COST SAVINGS WITH DMT REDESIGN OF FOUNDATION SYSTEM
Westminister Village	$100,000
Ocean Landing Shopping Center	$750,000
Old Town Crescent	$150,000
Fox Run Village	$100,000
Monarch Landing	$150,000
MD Live!	$2,000,000
Towson Circle	$200,000
Retirement Community, Glen Mills, PA	$150,000
Xfinity Live!	$500,000
Obery Court	$200,000
Residences at Rivermarsh	$100,000
Residences at River Place	$80,000
Ocean Pines	$200,000
Four Seasons	$100,000
912 King Street-116 S Henry Street Mixed Use	$500,000
Dumfries Town Square	$200,000

Seacobeck Hall—Mary Washington University	$500,000
Motown	$150,000
Richmond Area Collegiate Science Building	$85,000
Richmond Area Collegiate Research Building	$150,000
Food Processing Addition and Tank Farm	$100,000
13th and U Street	$100,000
55 M Street	$150,000
Alexan Dunn Loring Development	$250,000
Association of Manufacturing Technology Building	$150,000
Excelsior Parc Development	$100,000
Glenmont WMATA	$150,000
Halley Rise	$150,000
Howard Hughes HHMI Expansion	$100,000
I-64 Widening	$500,000
JHU-NIH-NCI	$150,000
Mark Center Plaza Building 5	$150,000
Mosaic Parcel CE	$100,000
National Gateway Land Bay "E" West	$250,000
Potomac Yard Bay D	$150,000
Ripley Street Development	$100,000
Rock Spring Centre	$250,000
Route 7 over Dulles Toll Road	$150,000
Route 7 Widening	$350,000
Tysons Archstone	$150,000
Tysons Central	$250,000
Upper Rock Blocks G & H	$100,000
West Falls Church WMATA	$150,000
McWane Hall—Lynchburg College	$100,000
Brooktrout	$50,000
Mecklenburg Schools	$100,000
Abingdon Elementary School	$225,000
Abingdon Heights	$400,000
Fauquier High School	$250,000
Prince William Commons	$400,000
PWCPS Administration Bldg	$225,000
Warrenton Aquatic & Recreation Facility	$250,000
Washington Center	$350,000
WMATA White Flint Parking Garage	$625,000
3800 Glenwood	$350,000
Homewood Suites	$150,000
Johnson County WWTP	$1,000,000
1011 M Street	$200,000
14th and W Street	$200,000
1600 7th Street	$50,000
300 8th Street	$125,000
A-1 Glass	$100,000
B-CC High School	$350,000
Carlisle	$200,000
Fairfax Blvd Center	$100,000
Forest Oak Middle School	$100,000
Grimke	$150,000
Kilmer Place	$50,000
Liberty Tank	$100,000
Sumner Suites	$125,000
Windsor	$50,000
Wood Middle School	$75,000
Wootton	$75,000
14th and P Street	$150,000
Culpepper Farmers' Coop	$50,000
Indian Head Water Tanks	$75,000
Portals Phase 3	$175,000
Thomas Jefferson Library	$75,000
Avalon Mosaic Parcel H	$800,000
Cabin John Middle School	$200,000
Navy Federal Credit Union	$100,000
Cambridge Village	$150,000
Ben Oaks Water Tower	$75,000
Apple Greene Water Tower	$50,000
Oyster Bay Condos	$100,000
North Beach Various Parcels	$50,000
Fort Meade-DINFOS	$200,000
Fort Meade-Building #8605	$50,000
Fort McNair-Building #48	$250,000
535 Broadwater Road	$50,000
15 Judith Sound Circle	$8,000
318 Ironside Circle	$50,000
Courthouse Professional Building	$60,000
Dahlgren Hotel	$75,000
Doc Stone MOB	$40,000
Hamptons at Hunton Park	$60,000
Kaeser Compressors Warehouse Expansion	$80,000
New Post Site	$50,000
Oakwood Estates	$85,000
Sophia and Hanover Streets	$40,000
1112 First Street Hotel	$250,000
Courthouse Village Bridge	$250,000
Arbor House	$100,000
William Square Hotel	$250,000
James Madison University—Phillips Hall	$150,000
1336 H Street	$80,000
Aspire at Lee's Hill	$35,000
DHL Stafford	$25,000
Mapledale Storage	$50,000
Pruitt Laburnum Property	$80,000
Wilson YMCA	$250,000
Multi-Story Residential—Richmond, Virginia	$50,000
Industrial Complex—Hanover, Virginia	$250,000
Tank Farm—Cumberland, VA	$30,000
Industrial Facility—Eastern NC	$100,000
Industrial Facility—King William, Virginia	$50,000
Industrial Facility—King William, Virginia	$100,000
Multi-Story Office and Parking—Richmond, Virginia	$75,000
3700 National	$250,000
Andrews Air Force Base	$100,000
Potomac Yard Land Bay "F"	$250,000
Waterfront Station	$150,000
Rustburg Middle School	$200,00
Mechlenburg Middle/High Schools	$200,000
Annapolis Junction Building 3	$250,000
Annapolis Junction Building 4	$250,000
116S Henry Street	$750,000
QTS	$500,000
Reston Crescent	$90,000
Total Cost Savings	**$25,053,000**

5. Conclusions

1. The dilatometer test statically deforms the soil. Using the triangulation method, the dilatometer test with its two measured independent variables (P_0 and P_1) accurately correlates with the soil's constrained deformation modulus.
2. A dilatometer test sounding provides a deformation modulus profile that includes thin soft layers that may be critical to settlement analyses. Each sounding

therefore becomes a settlement prediction.

3. Penetration tests (SPT and CPT) with a single independent variable of probe resistance that strain the soil to failure with a circular projection do not accurately correlate with the soil's deformation modulus.
4. 125 projects demonstrate how the dilatometer test data saved the owners $24,863,000 over the previously overly conservative designs based on less accurate tests.
5. My valuable clients provided estimates for the cost savings presented in Table 1. Their input greatly improved the paper, and I am grateful for their support.

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